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TRANSITION IN A BOUNDARY LAYER AND IN A PIPE FLOW.(U)

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Transition in a Boundary Layer and in a Pipe Flow

I. Wygnanski

I Introduction

The structure of turbulent shear flows has been the object of an enormous research effort. Initially, the mean flow field was mapped and the data served to construct prediction-models of the "mixing-length" and "eddy-viscosity" type. When the shortcomings of those models became obvious, more sophisticated measurements which included statistical quantities of the turbulence field were reported in the literature. These, in turn, led to improvements in modeling which consider now the balance of turbulent energy or/and the time required for decay of certain eddy sizes. All models, however, include a number of arbitrary constants which are altered from flow to flow or from region to region of the same flow. These constants represent a measure of our ignorance and their number increases with the level of sophistication of the model.

Some physical phenomena which are characteristic of turbulent shear flows were observed: (i) The existence of a well defined interface which separates the turbulent fluid from its environment.

(ii) The existence of large scale structures which are responsible for most of the vigorous transport phenomena associated with turbulent shear flows.

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(iii) The intermittency of the small scale dissipative structure.

(iv) The intermittent (patchy) transition from laminar to turbulent flows.

We have decided to study in detail the latter phenomenon because it contains all the features of fully turbulent flows; it is more orderly; it represents a change from a flow which is represented by a solution of the equations of motion (e.g., laminar boundary layer) to a flow which can, at best, be represented by a set of model equations; and it was not as extensively investigated as the fully developed turbulent flows because of its unsteady nature which requires highly sophisticated measuring sensors and data acquisition techniques.

II. A Brief Description of the Findings in Transitional Pipe Flow

At first we studied transition in a pipe flow because we thought that an axisymmetric flow will be simpler to map and analyze than a three dimensional configuration (an assumption which proved to be wrong). The The findings are reported in a paper by Wygnanski and Champagne (1973). Some of the highlights are listed below:

(1) A surprisingly high transition Reynolds number (based on the pipe diameter and an average velocity in the pipe $Re_{TR} > 6{*}10^4$) can be obtained in a commercially available aluminum pipe provided there are no steps at the joints and the flow at the entrance is free of large perturbations.

(2) Poiseuille type flow (i.e., fully developed laminar flow having a parabolic velocity profile) actually never became turbulent because transition was preempted by the fact that the pipe was never long enough to retain a parabolic profile. Since the criterion determining the inlet length of a pipe is given by $x/DRe \gtrsim$ constant, for a pipe of fixed geometry the inlet region increases in length with increasing Re. Only after the fully developed region vanished transition occurred in the boundary layer. Preliminary observations indicated that the initial breakdown process is very similar to that in a boundary layer on a flat plate.

(3) A turbulent slug which results from transition in a boundary layer (at $Re \gtrsim 3000$) occupies the entire cross section of a pipe and is comparable in length with the pipe. The slug grows in length as it proceeds downstream by entraining laminar fluid. The interior of a slug is identical to a fully developed turbulent pipe flow, but at the edges there is an enhanced turbulent activity. Energy considerations suggest that

turbulence propagates into non-turbulent fluid by diffusion.

(4) A unique relation exists between a velocity of a given interface and the velocity of a fluid which prevents any turbulent fluid from leaving the slug. This observation was later extended to other flows.

(5) When a large stationary disturbance is introduced near the inlet of the pipe the flow becomes locally turbulent. (This type of transition has nothing in common with the pipe or a boundary layer because the flow is forced to separate by the disturbance and free shear layers are very unstable.) The pipe flow slowly returns to its laminar state provided Re $<$ 2000. (Consequently, Re $\approx$ 2000 is the highest Reynold number for which the pipe flow remains stable to <u>any</u> kind of disturbance, large or small.) This leads one to conclude that one should not expect a small perturbation stability calculation to show amplification at this Re even if the calculation includes non-linear terms. With the large disturbance at the inlet, the flow becomes fully turbulent at Re $\approx$ 3000 but at Re $\approx$ 2000 it is intermittent. At Re = 2250 a steady state is attained for which the turbulent regions neither grow nor decay. These turbulent regions which we called "puffs" were the subject of our second investigation (Wygnanski, Sokolov and Friedman (1975)). It was observed that (a) All puffs at the same Re are of equal length implying that the puff must be the most basic turbulent module in transitional pipe flow rather than a slug (it should be analogous to the turbulent "spot" in a boundary layer).

(b) The turbulent intensity in the puff increases gradually towards the rear interface where it attains a maximum. It is also concentrated in the central region of the pipe rather than near the wall.

(c) By processing the data digitally the accuracy of determining the location of the trailing interface in the central region of the pipe was better than 0.003 seconds, corresponding to a spatial resolution of approximately 0.07D (D being the diameter of the pipe) while the length of the puff is approximately 25D. This enabled a detection of a large "eddy" within a puff which may be represented by a toroidal vortex located near the trailing interface. Most of the turbulent energy eminates from the center of this vortex.

(d) By increasing the Reynolds number slightly the "puff" tends to split by leaving the last large eddy (toroidal vortex) behind. Turbulent energy considerations lead one to believe that the splitting of a puff is caused by negative production which is related to the flow field induced by the toroidal eddy.

We made an attempt to control the splitting by regulating its occurrance in terms of time and space but so far we were not successful. It is believed that successive splitting leads to secondary breakdown and to the relationship between puffs and slugs. We were able to determine by introducing disturbances far away from the inlet at low Re that both forms of transition (i.e., puffs and slugs) can exist in a fully developed pipe flow and not just in the inlet region. The investigation of transition in a pipe still continues because it is believed that the puff plays the same role in a fully developed turbulent pipe flow as the spot does in a boundary layer. Perhaps there is actually a relationship between the two which is simply masked by the different geometries.

III. A Brief Description of the Findings in a Boundary Layer

Although the turbulent spot in a laminar boundary layer was investigated previously by Schubauer and Klebanoff (1956) we decided to repeat the investigation in greater detail. It was established that:

(1) The spot attains a universal shape some distance downstream of the disturbance that generates it. The shape of the spot appears to be independent of the thickness of the laminar boundary layer surrounding the spot and the local Reynolds number.

(2) The propagation velocity of the trailing interface of the spot is approximately constant and equal $0.5\ U_\infty$ (U_∞ is the freestream velocity). The propagation velocity of the leading interface is approximately $0.9U_\infty$ near the centerline of the spot but it tapers off with increasing spanwise location. Near the "wing-tip" (looking at the spot in its plan view) the propagation velocity of the leading interface approaches the propagation velocity of the trailing interface. This may be an important finding since it implies that two spots generated side by side (i.e., at different spanwise locations) should retain some of their identity very far downstream. The identifiable region will be limited to the central portion of the spot near its leading interface.

(3) Velocity measurements inside the spot indicated that spots of similar shape also represent similar velocity fields. This enabled us to calculate typical boundary layer parameters (e.g., momentum thickness, displacement thickness, etc.) for the spot.

(4) The turbulent velocity profile within the spot obeys the universal logarthmic relationship for the wall region but does not obey the "outer law" implying that there may be only one length scale associated

with the "spot" while there are two length scales associated with a turbulent boundary layer.

(5) The stream lines on the plane of symmetry of the spot in a frame moving at either interface indicate again that an interface always entrains non-turbulent fluid.

(6) The spot may be regarded as a large eddy which is convected at an intermediate velocity of $0.65U_{\infty}$. The observations associated with the spot have some resemblance to the visual observations made by Offen and Kline in a turbulent boundary layer.

After mapping the transitional spot in an otherwise laminar boundary layer, we explored further a possible relationship between the coherent structure in a fully-developed, turbulent boundary layer and the transitional spot. After all, the turbulent boundary layer is generated *initially* by the merging of such spots. This, however, represents a fairly substantial deviation from tradition which suggests that the "life-span" of a large eddy does not exceed 5 boundary layer thicknesses. In the experiment reported by Zilberman, et. al. (1977) a marked transitional spot was followed after it penetrated the turbulent boundary layer over a distance of approximately 100 initial boundary layer thicknesses without the use of arbitrary threshold criteria. Furthermore, since there was no appreciable deterioration in the signal with distance it would appear that the transitional spot could be tracked indefinitely in a turbulent boundary layer at those moderate Reynolds numbers. The structure, thus, resolved against the background of the mean turbulent velocity profile is characterized by a region of velocity defect in the outer part of the boundary layer, which approaches the wall as one proceeds in the spanwise direction from the centerline of the structure. A relatively narrow region of velocity excess is concentrated near the centerline and the wall. The overall structure is convected downstream at a speed equal to 90% U_∞. Thus, all features measured are in detail agreement with the conditionally sampled observations at the outer part of the turbulent boundary layer and are also in accord with the correlation measurements in the wall region. Representations of the flow pattern in a coordinate system traveling with the spot show temporal sequences similar to those visualized using dye techniques. Thus, it was possible to map quantitatively the structure of the large eddy in a turbulent boundary layer. Moreover the link between the transitional spot and the coherent eddy structure in a turbulent boundary layer may provide a new approach towards a more fundamental understanding and modeling of the turbulent boundary layer itself which will, hopefully, remove some of the empiricism currently used.

IV. Research Currently in Progress

An interaction study between adjacent spots is currently under way in Tel-Aviv. The purpose of this study is to explain how a transitional spot which continuously spreads in a laminar boundary layer is reduced to its observed dimensions in a turbulent boundary layer.

While searching for a possible mechanism which would explain the generation of small scale eddies within a spot, we discovered at USC a relationship which could link the growth of a spot to Tollmien-Schlichting stability theory. A wave train was observed trailing the transitional spot at its "wing tips" (i.e., away from the plane of symmetry). This wave train travels at a velocity at which the most unstable Tollmien-Schlichting waves would travel at that Reynolds number and the waves in it possess the correct frequency. This could be a very important finding because the relationship between transition and Tollmien-Schlichting waves was not clearly identified in the past. Only after Tollmien-Schlichting waves were introduced into the boundary layer artifically with a vibrating ribbon they were observed to amplify and breakdown, but even then, the relation between the amplification of the unstable waves and the breakdown to turbulence was not well established.

Figure 1 shows velocity traces obtained from a rake of 12 hot wires which are placed in the transverse direction, the wave train following the spot is obvious from the figure.

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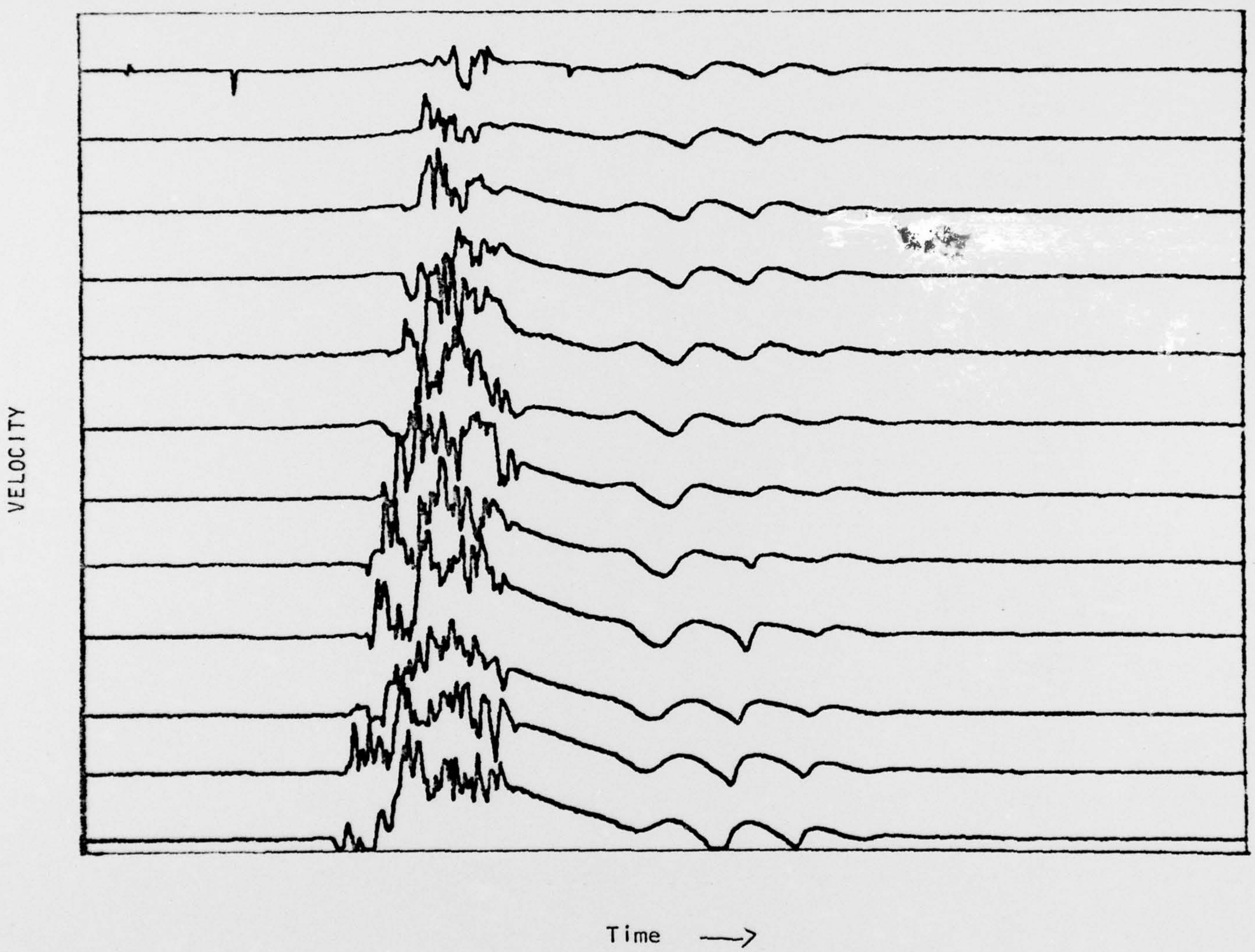

Figure 1 Note: Origin shifted in the vertical direction

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An experimental investigation was carried out in shear flows undergoing transition to turbulence and in fully developed turbulent flows. The aim of the experiment is to understand and control transition, as well as to determine the effects of transition on fully turbulent flows. In the boundary layer case this effect was clearly established at moderate Reynolds numbers.

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